Fast and slow responses of the South Asian monsoon system to anthropogenic aerosols

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[1] Using a global climate model with fully predictive aerosol life cycle, we investigate the fast and slow responses of the South Asian monsoon system to anthropogenic aerosol forcing. Our results show that the feedbacks associated with sea surface temperature (SST) change caused by aerosols play a more important role than the aerosol's direct impact on radiation, clouds and land surface (rapid adjustments) in shaping the total equilibrium climate response of the monsoon system to aerosol forcing. Inhomogeneous SST cooling caused by anthropogenic aerosols eventually reduces the meridional tropospheric temperature gradient and the easterly shear of zonal winds over the region, slowing down the local Hadley cell circulation, decreasing the northward moisture transport, and causing a reduction in precipitation over South Asia. Although total responses in precipitation are closer to the slow responses in general, the fast component dominates over land areas north of 25°N. Our results also show an east-west asymmetry in the fast responses to anthropogenic aerosols causing increases in precipitation west of 80°E but decreases east of it. **Citation:** Ganguly, D., P. J. Rasch, H. Wang, and J. Yoon (2012), Fast and slow responses of the South Asian monsoon system to anthropogenic aerosols, *Geophys. Res. Lett.*, *39*, L18804, doi:10.1029/2012GL053043.

1. Introduction

[2] Climate response to a forcing agent such as anthropogenic aerosols can be conceptualized as a combination of a fast and a slow component [*Hansen et al.*, 2005; *Bala et al.*, 2009; *Andrews et al.*, 2010]. The responses that are induced through the direct impact of aerosols on radiation, clouds and land surface (rapid adjustments) are often identified as the fast component, whereas, responses to global surface temperature change induced by changes in aerosol emissions are termed as the slow component. *Andrews et al.* [2010] showed that the fast component of the global annual mean precipitation response to a range of forcing agents including major anthropogenic aerosol species, correlates with the atmospheric component of radiative forcing, while the slow component of the global annual mean precipitation response is generally independent of the climate change mechanism and found to have an about 2–3% increase per unit of global surface temperature change [*Allen and Ingram*, 2002; *Held and Soden*, 2006; *Bala et al.*, 2009; *Andrews et al.*, 2010].

[3] While it is useful and conceptually easier to understand these responses in terms of their global annual mean values, it is also important to understand the regional characteristics of fast and slow responses to anthropogenic aerosols which perturb both surface and atmospheric energy balance of the Earth. This is needed because unlike the well distributed long-lived greenhouse gases, aerosols have shorter residence time, diverse physical properties, heterogeneous distribution around the globe, and aerosol radiative forcing exhibits large spatiotemporal variability. Analyzing the fast and slow responses separately helps in understanding the relative strengths of different pathways of aerosol impact on major precipitation systems such as the South Asian monsoon. *Ramanathan et al.* [2005] showed that the reductions in surface solar radiation due to absorption and scattering by aerosols ("solar dimming") cools the northern Indian Ocean, reduces evaporation, causes a spin down of the local Hadley cell circulation, and weakens the Indian summer monsoon precipitation. Subsequent modeling studies have confirmed this pathway, and more recent studies show the monsoon response to "solar dimming" is not only caused by direct effect of aerosols but also augmented by their indirect effects [*Chung and Ramanathan*, 2006; *Meehl et al.*, 2008; *Cowan and Cai*, 2011; *Bollasina et al.*, 2011; *Ganguly et al.*, 2012]. But, *Lau et al.* [2006] suggested a different pathway, according to which shortwave (SW) heating by absorbing aerosols over northern India and the Tibetan plateau can act like an "elevated heat pump" (EHP), enhancing the meridional temperature gradient in the mid-to-upper troposphere, increasing the moisture convergence over India and causing an advancement and intensification of the monsoon precipitation. Although the viability of the EHP mechanism has been recently debated [*Nigam and Bollasina*, 2010; *Lau and Kim*, 2011], various modeling studies have indicated signatures of the EHP mechanism in their simulations, but found it relevant only in the late boreal spring and early summer [*Meehl et al.*, 2008; *Randles and Ramaswamy*, 2008; *Cowan and Cai*, 2011; *Ganguly et al.*, 2012]. *Wang et al.* [2009] showed that absorbing anthropogenic aerosols could also impact the South Asian summer monsoon precipitation through their influence on the moist static energy in the sub-cloud layer.

[4] While *Ganguly et al.* [2012] investigated the contribution of important components of present day aerosol forcing, this study elucidates the contribution of fast responses versus responses to SST changes induced by changes in aerosol emissions (defined as the slow component) in shaping the total equilibrium climate response of the South Asian monsoon system to anthropogenic aerosol forcing. Our study also provides a physically-based plausible explanation for the noted asymmetry in trends of seasonal mean monsoon rainfall between eastern and western

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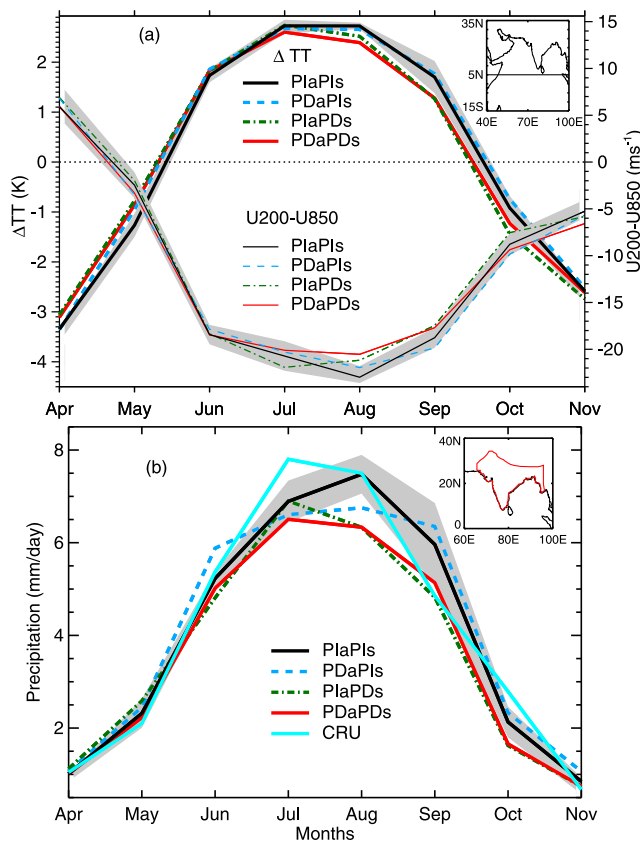
Figure 1. Comparison of climatological monthly mean (a) tropospheric temperature gradient (ΔTT) between the two boxes within the inset, vertical shear of zonal winds ($U_{200} - U_{850}$) and (b) precipitation rate (mm/day) averaged over the South Asian region (as shown in the inset) from different experiments discussed in this study and Climate Research Unit (CRU) observations (average over the years 1995 to 2004). Gray shading in all panels represents a 90% confidence interval for the results from our control experiment (PIaPIs) based on statistical test.

segments of the sub-continent during past few decades [*Konwar et al.*, 2012].

2. Experiment Design and Methodology

[5] We used the atmospheric component of the Community Earth System Model (CESM1, released version 1.0.2), which is the Community Atmosphere Model (CAM5) having a hydrostatic, finite-volume (FV) dynamical core with a horizontal resolution of 1.9° latitude × 2.5° longitude and 30 vertical levels [*Neale et al.*, 2010; *Ganguly et al.*, 2012]. We perform Hansen style "fixed-SST" experiments [*Hansen et al.*, 2005] with appropriate combinations of aerosol emissions and prescribed SST data (from coupled simulations of *Ganguly et al.* [2012]) to separate the slow and fast responses to aerosol forcing. Four numerical experiments are designed to examine the responses to changes in emissions of aerosols from the preindustrial (defined as year 1850) to present day (defined as year 2000). All other forcing agents (greenhouse gases, ozone, solar and land surface properties) are fixed at preindustrial levels. We used the same emission

inventories for aerosols and other radiatively active gaseous species as *Ganguly et al.* [2012].

[6] Our control simulation (PIaPIs) uses aerosol emissions at preindustrial levels and a prescribed annual cycle of monthly mean SST distribution corresponding to preindustrial conditions produced by averaging monthly output from the last 100 years of unforced model integration under equilibrium from case PI in *Ganguly et al.* [2012]. Experiment PDaPIs includes aerosol emissions at present day levels while the prescribed SSTs are same as used in PIaPIs. Experiment PIaPDs uses preindustrial emissions and a prescribed annual cycle of monthly mean SSTs that differ from the earlier two experiments only by replacing the SSTs with those from the coupled simulation of *Ganguly et al.* [2012] that included present day aerosol emissions. Experiment PDaPDs uses present day aerosol emissions, while the prescribed SSTs are same as used in PIaPDs. Each of these experiments are run for 31 model years and the results from the last 30 years of simulation are analyzed for climate responses. The prescribed SSTs, while fixed from year to year in each experiment, vary monthly over the annual cycle.

[7] Fast (Slow) responses are estimated by differencing results from experiments PDaPIs (PIaPDs) and PIaPIs. Note, that the results from equilibrium climate change experiments described in *Ganguly et al.* [2012], performed using the coupled atmosphere-mixed layer ocean model can be considered as the full climate response to aerosol forcing [*Bala et al.*, 2009; *Andrews et al.*, 2010]. But, here we estimated the total response to aerosol forcing by differencing results from experiments PDaPDs and PIaPIs.

3. Results

[8] Earlier studies have shown that one of the robust signatures of South Asian monsoon onset (withdrawal) corresponds to a positive (negative) meridional tropospheric temperature (denoted as TT, averaged between 200 hPa and 600 hPa) gradient [*Goswami and Xavier*, 2005; *Xavier et al.*, 2007]. We define the difference ΔTT between a northern box (40–100°E, 5–35°N) and a southern box (40–100°E, 15°S–5°N) following *Xavier et al.* [2007]. The strength of the monsoonal circulation over the region is also associated with a strong easterly shear of zonal winds [*Goswami and Xavier*, 2005]. Figure 1a shows the evolution of climatological monthly mean ΔTT and the vertical shear of zonal winds ($U_{200} - U_{850}$, averaged over 50–95°E, 0–15°N) from different experiments. We find that the aerosol forcing reduces the crucial ΔTT as well as the magnitude of $U_{200} - U_{850}$ from July to October period in a way that slows down the monsoon circulation, resulting in a decrease in JJAS (June to September) mean area averaged precipitation over South Asia (see Figures 1a and 1b). Our decomposition of responses reveals that the decrease in ΔTT and $U_{200} - U_{850}$, particularly in the later part of the monsoon period is mostly a manifestation of the slow response to aerosol forcing and induced through the inhomogeneous SST cooling with weakened summertime north-south SST gradient over the Indian Ocean as shown in *Ganguly et al.* [2012]. When the SST is not allowed to respond to the aerosol forcing (case PDaPIs), ΔTT increases in the month of May (similar to EHP mechanism) but it is not sufficient to cause a significant increase in area mean precipitation during
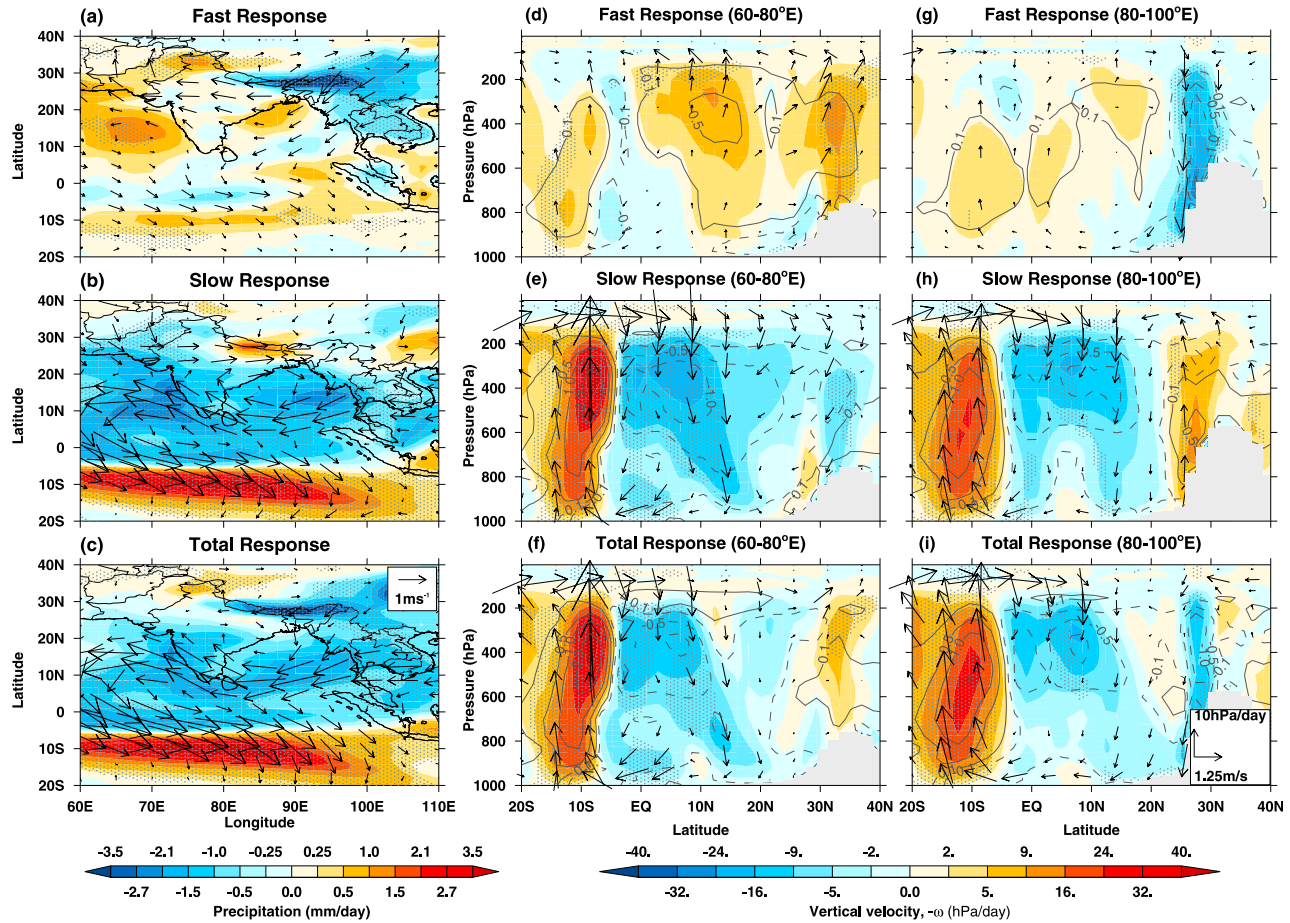
Figure 2. JJAS mean (a) fast, (b) slow, and (c) total responses in precipitation and wind vectors at 860 hPa to present day aerosol forcing. JJAS mean (d and g) fast, (e and h) slow, and (f and i) total responses in meridional circulation depicted by (v, $-\omega$), where v (m/s) is the meridional velocity and $-\omega$ (hPa/day) is the vertical velocity averaged over 60–80°E and 80–100°E. Responses in diabatic heating rates are also shown as black contour lines drawn with intervals as 0.1, 0.5, 1.0, and 2.0 K/day in these panels. Here dotted contours indicate cooling and solid contours indicate heating. Stipples in all panels represent areas where the anomalies (in precipitation or vertical velocity) are at or exceed the 90% confidence level based on the Student's t-test. Responses in diabatic heating rates are also above the 90% confidence level.

the same month as ΔTT remains negative, albeit area mean precipitation increases in June (Figures 1a and 1b).

[9] Figures 2a–2c show the spatial distribution of JJAS mean fast, slow and total precipitation response over a portion of Asia to aerosol forcing. Major characteristics of the total precipitation response estimated in our present study are very similar to the responses corresponding to PD case in *Ganguly et al.* [2012]. Decomposition of the total response into fast and slow components indicate that almost all of the precipitation reductions over India (south of 25°N), Arabian Sea, and Bay of Bengal are a result of the slow response to aerosol forcing, whereas increases in precipitation over the north-western part of the subcontinent as well as decreases over north-east India and Nepal region are due to the fast response to aerosol forcing. The spatial distribution of fast, slow, and total precipitation responses reveal a kind of east-west asymmetry over South Asia, particularly over land areas north of 25°N. Interestingly, the characteristics of this asymmetry is opposite for fast and slow components. For example, in the case of fast responses, more areas west of 80°E experience increases in precipitation, while more areas east of 80°E experience decreases in precipitation. Over

South Asia, we also find that the total responses in precipitation are closer to its slow component in areas south of 25°N, while the fast component dominates north of this latitude. Total responses are often weaker than either fast or slow components, indicating partial cancelation of these responses, owing to their opposite characteristic over most areas.

[10] In order to understand the physical processes leading to such east-west asymmetry in fast and slow precipitation responses, it is essential to examine the dynamical aspects of these responses separately on both sides of 80°E. Figures 2d–2f show the JJAS mean fast, slow and total responses in meridional circulation and net diabatic heating rate averaged over 60–80°E. Changes in vertical velocities are caused by gain or loss of energy by the atmosphere, mostly through diabatic heating or cooling processes. Over 60–80°E and north of 10°N, fast responses in net diabatic heating rate is mostly positive in the middle and upper troposphere (above 800 hPa), resulting in increased upward motion over this region (Figure 2d). While the lower and middle tropospheric region between 10°S and 10°N, experiences decrease in rising motion associated with a drop in net diabatic heating rate. The increase
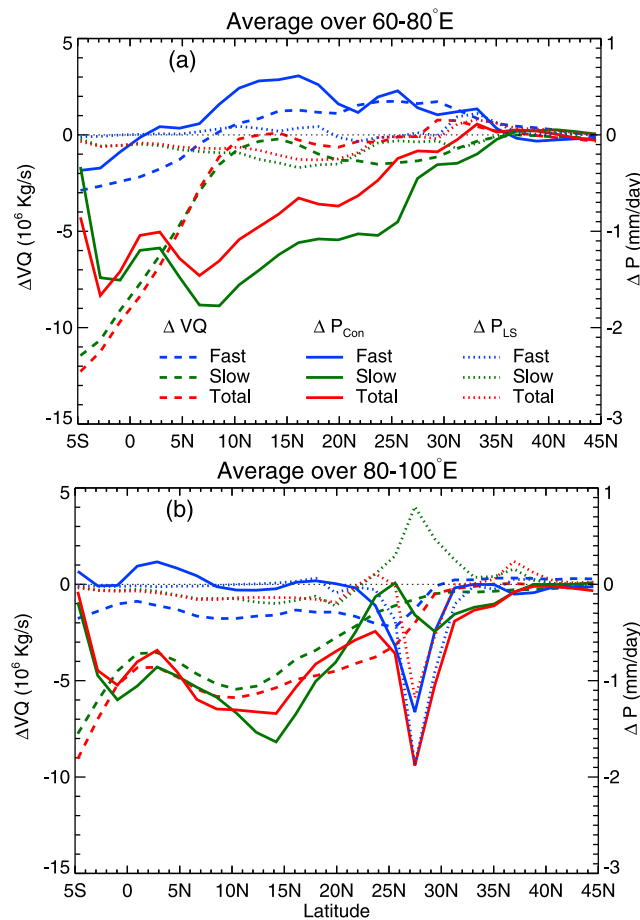
Figure 3. Fast, Slow and Total response in JJAS mean column integrated meridional water vapor transport (ΔVQ), convective precipitation (ΔP_{Con}), large scale precipitation (ΔP_{LS}) averaged over (a) 60–80°E, (b) 80–100°E.

in net diabatic heating rate in the middle and upper tropospheric region north of 10°N and west of 80°E is contributed by increased SW absorption by aerosols (see Figure S1 in the auxiliary material) and increased moist convection.[1] SW absorption by aerosols is found to be most effective over the north-western part of the subcontinent owing to its unique topography (less steep and lower altitude over a large area compared to the eastern sector due to curvature along the southern edge of the Tibetan Plateau west of 80°E) and the reinforcement of the meridional circulation in that region during summer monsoon which is capable of lifting the aerosols to higher levels above the mountains. Thus the fast component of the meridional circulation response over 60–80°E in our model is similar to the EHP mechanism hypothesized by *Lau et al.* [2006], increasing the precipitation in this sector (Figures 2a and 2d). Contrary to the fast component, the slow response in meridional circulation on the west side of 80°E is characterized by large increase in upward motion south of the equator in the Indian ocean region ($\sim$5–20°S) from the surface up to almost the tropopause level and relative subsidences (or decreased upward motion) in the areas north of it (Figure 2e). Although, fast responses are generally overwhelmed by the

slow responses in meridional circulation on the western sector (60–80°E) from south of the equator up to almost 25°N, we still see signatures of increased upward motion over the north-western part of the Indian subcontinent in the total circulation response (Figure 2f).

[11] The most striking difference in circulation response east and west of 80°E comes from differences in the fast components, with the mid-to-upper tropospheric circulation getting reinforced over 60–80°E and north of the equator, while significant decrease in upward motion is noted along the southern slopes of the Himalayas over 80–100°E (Figures 2d and 2g). There is stronger topographic lifting and more large scale precipitation east of 80°E and north of 25°N where the topography is steeper and higher. As the fast response in lower tropospheric winds over this region is opposite to the climatological south-westerlies, it significantly reduces the topographic lifting along the upward limb of the local Hadley cell circulation on east of 80°E and decreases precipitation over the region (Figures 2a and 2g). Another factor, which is partly responsible for this reduction in precipitation in the fast component, is due to increased cloud lifetime in the polluted atmosphere and a reduction of warm-phase orographic precipitation along the upslope on the windward side of the mountains [*Rosenfeld et al.*, 2007]. We find that as a fast response to aerosol forcing, although the average condensate number concentrations increases along the southern slopes of the Himalayas, there is a decrease in average rain number concentration (Figure S2), likely associated with increased cloud lifetime effect, contributing to the reduction in precipitation over this region. In contrast to the fast component, the slow response in lower tropospheric winds reinforces the climatological south-westerlies over this region (east of 80°E), resulting in increased topographic lifting and precipitation (Figures 2b and 2h). Most other features in the slow component of circulation response on either side of 80°E and south of about 25°N are similar.

[12] Thus the fast component of the model's circulation response over 60–80°E increases the moisture convergence into the subcontinent and precipitation in this sector (Figure 3a). While the slow component of the response slows down the local Hadley cell circulation, decreasing the northward moisture transport, and causing a large reduction in precipitation on both sides of 80°E. Although increases in the northward moisture transport and precipitation over 60–80°E as part of the fast response are smaller in magnitude compared to their decreases on both sides of 80°E in the slow response, increases in average precipitation are significant (above the 90% confidence level based on the Student's t-test) over 10–18°N and over 25–35°N (Figures 2a and S3). Both fast and slow responses decrease the northward moisture transport on the east side of 80°E but slow component responses are mainly manifested in a reduction in precipitation up to about 25°N, while fast component responses in precipitation are found in areas north of it through mechanisms discussed earlier.

[13] Based on reanalysis data, *Konwar et al.* [2012] attributed the decreasing and increasing trend in moisture transport over the Bay of Bengal and the Arabian Sea respectively as the likely reason for the noted decreasing and increasing trend in low and medium rainfall over the eastern and the western parts of India during recent decades. Results of our modeling study suggest that the east-west asymmetry in the fast component of atmospheric circulation responses to aerosol forcing resulting decreased northward moisture

transport into the subcontinent on its east while increases in the west could be at least in part responsible for the observed asymmetry in trends of seasonal mean monsoon precipitation between eastern and western segments of the subcontinent noted by *Konwar et al.* [2012]. A fast response in the model's meridional circulation is found west of 80°E during the summer monsoon, similar to the EHP mechanism hypothesized by *Lau et al.* [2006], resulting in increased moisture convergence into the subcontinent. East of 80°E, this component of the fast response is overwhelmed by other components, for example those due to cloud lifetime effects and reduced topographic lifting along the southern slopes of the Himalayas. These contribute to the weakening of the large scale meridional circulation and result in decreased moisture convergence into the subcontinent.

4. Conclusions and Discussions

[14] Our decomposition of total responses into fast and slow components shows that the feedbacks associated with SST change caused by anthropogenic aerosols play a more important role than the aerosol's direct impact on radiation, clouds and land surface (rapid adjustments) in shaping the equilibrium climate response of the South Asian monsoon system to aerosol forcing. Weakened summertime north-south SST gradient over the Indian Ocean by aerosol induced spatially inhomogeneous SST cooling eventually reduces the meridional tropospheric temperature gradient and the easterly shear of zonal winds over the region. This slows down the local Hadley circulation, decreases the northward moisture transport, and reduces precipitation over South Asia. Although slow responses are generally stronger, the fast responses in precipitation dominates over land areas north of 25°N. The response of the South Asian monsoon system to anthropogenic aerosols is multi-scale in nature. The EHP mechanism proposed by *Lau et al.* [2006], "solar dimming" shown by *Ramanathan et al.* [2005], and the aerosol indirect effects all play important and different roles. Our study shows that the responses through the EHP mechanism are a part of the fast component, while responses due to "solar dimming" constitute the slow component response to aerosol forcing. As these fast and slow responses emerge on different timescales, and the responses through the EHP mechanism, being generally weaker and opposite in characteristics, are largely masked by the slow responses as well as those due to cloud lifetime effect. Our results also suggest that an east-west asymmetry occurs in the fast component of atmospheric circulation responses to aerosol forcing with decreased northward moisture transport into the Indian subcontinent to the east and increases to the west could, at least in part be responsible for the observed asymmetry in trends of seasonal mean monsoon precipitation over recent decades. We note that aerosol emissions in our simulations are likely underestimated over this region, but we believe the main conclusions will remain unchanged, with higher emissions (see, e.g., *Ganguly et al.* [2012], where doubling the carbonaceous aerosol emissions enhances the basic features of total response of monsoon precipitation, including the east-west asymmetry over land areas north of 25°N). Our findings are based on simulated aerosol distributions derived from standard emission inventories, discussed in *Ganguly et al.* [2012]. Constraining these simulated distributions to match

with observations would be useful in relating the simulated responses to observed trends in monsoon precipitation. We also note that although our objective in this study is focused on the fast and slow responses to anthropogenic aerosols, other forcing agents (e.g., greenhouse gases) will also play a role.

References

Allen, M. R., and W. J. Ingram (2002), Constraints on future changes in climate and the hydrological cycle, *Nature*, *419*, 224–232, doi:10.1038/nature01092.

Andrews, T., P. M. Forster, O. Boucher, N. Bellouin, and A. Jones (2010), Precipitation, radiative forcing and global temperature change, *Geophys. Res. Lett.*, *37*, L14701, doi:10.1029/2010GL043991.

Bala, G., K. Caldeira, and R. Nemani (2009), Fast versus slow response in climate change: Implications for the global hydrological cycle, *Clim. Dyn.*, *35*, 423–434, doi:10.1007/s00382-009-0583-y.

Bollasina, M. A., Y. Ming, and V. Ramaswamy (2011), Anthropogenic aerosols and the weakening of the South Asian summer monsoon, *Science*, *334*(6055), 502–505, doi:10.1126/science.1204994.

Chung, C., and V. Ramanathan (2006), Weakening of the North Indian SST gradients and the monsoon rainfall in India and the Sahel, *J. Clim.*, *19*, 2036–2045.

Cowan, T., and W. Cai (2011), The impact of Asian and non-Asian anthropogenic aerosols on 20th century Asian summer monsoon, *Geophys. Res. Lett.*, *38*, L11703, doi:10.1029/2011GL047268.

Ganguly, D., P. J. Rasch, H. Wang, and J.-H. Yoon (2012), Climate response of the South Asian monsoon system to anthropogenic aerosols, *J. Geophys. Res.*, *117*, D13209, doi:10.1029/2012JD017508.

Goswami, B. N., and P. K. Xavier (2005), ENSO control on the south Asian monsoon through the length of the rainy season, *Geophys. Res. Lett.*, *32*, L18717, doi:10.1029/2005GL023216.

Hansen, J., et al. (2005), Efficacy of climate forcings, *J. Geophys. Res.*, *110*, D18104, doi:10.1029/2005JD005776.

Held, I. M., and B. J. Soden (2006), Robust responses of the hydrological cycle to global warming, *J. Clim.*, *19*, 5686–5699, doi:10.1175/JCLI3990.1.

Konwar, M., A. Parekh, and B. N. Goswami (2012), Dynamics of east-west asymmetry of Indian summer monsoon rainfall trends in recent decades, *Geophys. Res. Lett.*, *39*, L10708, doi:10.1029/2012GL052018.

Lau, K. M., and K. M. Kim (2011), Comment on "'Elevated heat pump' hypothesis for the aerosol-monsoon hydroclimate link: 'Grounded' in observations?" by S. Nigam and M. Bollasina, *J. Geophys. Res.*, *116*, D07203, doi:10.1029/2010JD014800.

Lau, K. M., M. K. Kim, and K. M. Kim (2006), Asian summer monsoon anomalies induced by aerosol direct forcing: The role of the Tibetan Plateau, *Clim. Dyn.*, *26*, 855–864.

Meehl, G. A., J. M. Arblaster, and W. D. Collins (2008), Effects of black carbon aerosols on the Indian monsoon, *J. Clim.*, *21*, 2869–2882, doi:10.1175/2008JCLI2362.1.

Nigam, S., and M. Bollasina (2010), "Elevated heat pump" hypothesis for the aerosol-monsoon hydroclimate link: "Grounded" in observations?, *J. Geophys. Res.*, *115*, D16201, doi:10.1029/2009JD013800.

Ramanathan, V., et al. (2005), Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle, *Proc. Natl. Acad. Sci. U. S. A.*, *102*, 5326–5333.

Randles, C. A., and V. Ramaswamy (2008), Absorbing aerosols over Asia: A Geophysical Fluid Dynamics Laboratory general circulation model sensitivity study of model response to aerosol optical depth and aerosol absorption, *J. Geophys. Res.*, *113*, D21203, doi:10.1029/2008JD010140.

Rosenfeld, D., et al. (2007), Inverse relations between amounts of air pollution and orographic precipitation, *Science*, *315*(5817), 1396–1398, doi:10.1126/science.1137949.

Wang, C., D. Kim, A. M. L. Ekman, M. C. Barth, and P. J. Rasch (2009), Impact of anthropogenic aerosols on Indian summer monsoon, *Geophys. Res. Lett.*, *36*, L21704, doi:10.1029/2009GL040114.

Xavier, P. K., C. Marzin, and B. N. Goswami (2007), An objective definition of the Indian summer monsoon season and a new perspective on ENSO-monsoon relationship, *Q. J. R. Meteorol. Soc.*, *133*, 749–764, doi:10.1002/qj.45.